Fixed Point Dual Circular 32-QAM Performance for High Speed Wireless USB

Runfeng Yang[1], Jianyong Bian[2], Cailian Zhu[3]

Department of Electronic EngineeringDongguan Polytechnic Guangdong, China
[1]yangrf@dgpt.edu.cn; [2]bianjy@dgpt.edu.cn; [3]zhucl@dgpt.edu.cn

***Abstract*-The creation of Ultra-Wideband (UWB) radio platform has allowed the development of high bit-rate Wireless-USB offering High Definition video streaming. Quadrature Phase Shift Keying (QPSK) and Dual Carrier Modulation (DCM) are the current modulation schemes used for Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM) in the ECMA-368 defined UWB radio platform. ECMA-368 offers up to 480 Mb/s instantaneous bit rate to the Medium Access Control (MAC) layer to enable the high-rate transmission, but depending on radio channel conditions dropped packets unfortunately result in a lower throughput. This paper presents a higher data rate modulation scheme that fits within the configuration of the current standard to increase the system throughput by achieving 600 Mb/s (reliable to 3 meters) thus maintaining the high rate USB throughput even with a moderate level of dropped packets. The modulation system is termed Dual Circular 32-QAM (DC 32-QAM). The system performance for fixed point DC 32-QAM modulation is simulated in realistic multipath environments.**

Keywords-MB-OFDM; Frequency Diversity; DCM; Dual Circular 32-QAM

I. INTRODUCTION

USB is a fast and flexible serial bus interface standard to connect devices [1], offering a maximum bit rate of 480 Mb/s. It is designed to be easy for any users, with no user configuration required in hardware and software. The goals of USB include low cost, plug and play, expandable and hot plugging. A unique host in a USB system can support up to 127 devices. To handle many types of peripherals with varying requirements for transfer rate, response time and error correction, four types of USB data transfers are defined, being control transfer, bulk transfer, interrupt transfer and isochronous transfer all with different characteristics. Certified Wireless USB (W-USB) [2] is the new wireless extension to USB that combines the speed and security of wired technology with the ease-of-use of wireless technology. W-USB supports robust high speed wireless connectivity up to 480 Mb/s with low power targeting at 100 mW (whole physical device power) over a short distance by utilizing the common WiMedia MB-OFDM UWB radio platform as developed by the WiMedia Alliance [3].

UWB systems were recently proposed to standardize wide bandwidth wireless communication systems, particularly for Wireless Personal Area Networks (WPAN). The fundamental issue of UWB is that the transmitted signal can be spread over an extremely large bandwidth with a very low Power Spectral Density (PSD). In 2005 the WiMedia Alliance working with the European Computer Manufacturers Association (ECMA) announced the establishment of the WiMedia MB-OFDM (Multiband Orthogonal Frequency Division Multiplexing) UWB radio platform as their global UWB standard, ECMA-368 [4] and the latest updated version [5] incorporating spectral nulling. ECMA-368 was also chosen as Physical layer (PHY) of high data rate wireless specifications for high-speed Wireless USB.

Quadrature Phase Shift Keying (QPSK) and Dual Carrier Modulation (DCM) are exploited as standard modulation schemes for MB-OFDM in ECMA-368. QPSK constellation is used for data rates 200 Mb/s and lower while DCM is used as a multi-dimensional constellation for data rates 320 Mb/s and higher. However the maximum data rate of 480 Mb/s in a practical environment can not be achieved due to poor radio channel conditions causing dropped packets, resulting in a lower throughput and the need to retransmit the dropped packets. To increase the bit rate and allow for effective 480 Mb/s performance even with moderate packet loss in a practical system, rectangular Gray coded 16-QAM can be employed. However the system using the 16-QAM has no successful multipath propagation link for transmitting at 960 Mb/s or only achieves approximately 1 meter at 640 Mb/s comparing to the DCM 480 Mb/s mode and 320 Mb/s mode respectively (Appendix A). In this paper, a low cost and high performance modulation scheme termed Dual Circular 32-QAM (DC 32-QAM) is proposed, implemented and tested in fixed point model, which increases the MB-OFDM system throughput to 600 Mb/s (comparing to the DCM 480 Mb/s mode) with a successful link of 3 meters.

Chapter II presents the MB-OFDM background. Chapter III introduces DCM and 16-QAM. Chapter IV discusses DC 32-QAM mapping and demapping. Chapter V discusses consequential bit interleaver. Chapter VI discusses the performance measurements and comparisons while chapter VI presents the conclusions.

II. MB-OFDM IN ECMA-368

ECMA-368 specifies an MB-OFDM system occupying 14 bands with a bandwidth of 528 MHz for each band. The first 12 bands are grouped into 4 band groups (BG1-BG4), and the last two bands are grouped into a fifth band group (BG5). A sixth band group (BG6) containing band 9, 10 and 11 is also defined within the spectrum of BG3 and BG4, in agreement to usage

within worldwide spectrum regulations. The advantage of the grouping is that the transmitter and receiver can process a smaller bandwidth signal while taking advantages from frequency hopping.

At the heart of ECMA-368 lies a 128-pt IFFT resulting in each IFFT sub-carrier being clocked at 528MHz. The subcarriers in each OFDM symbol include 100 data subcarriers, 12 pilot subcarriers, 6 NULL valued subcarriers and 10 guard subcarriers. The 10 guard subcarriers used for mitigating Inter Symbol Interference (ISI) are located on either edge of the OFDM symbol and have same value as the 5 outermost data subcarriers. In addition, the guard carriers can be used as another form of time and frequency diversity resulting in improving receiver performance [6]. Each OFDM symbol is separated with a Zero Padded Suffix (ZPS) of 70.08ns to aid multipath interference mitigation and settling times of the transmitter and receiver.

To operate the PHY service interface to the Medium Access Control (MAC) service, a Physical Layer Convergence Protocol (PLCP) sublayer is defined to provide a method for converting a PSDU (PHY Service Data Unit) into a PPDU (PLCP Packet Data Unit) composed from three components (shown in Fig. 1): the PLCP preamble, the PLCP header and the PSDU. The PLCP preamble contains of two portions: a Packet/Frame Synchronization (PFS) sequence aimed at packet acquisition and detection, coarse carrier frequency estimation, coarse symbol timing and synchronization within the preamble; and a Channel Estimation (CE) sequence aiming at frequency response estimation, fine carrier frequency estimation and fine symbol timing.

To transmit a PSDU that contains the information bits, ECMA-368 has eight transmission modes by applying various levels of coding and diversity to offer 53.3, 80, 106.7, 160, 200, 320, 400 or 480 Mb/s. After bit interleaving, the coded and interleaved binary data sequence is mapped onto a QPSK or DCM complex constellation. The resulting complex numbers are loaded onto the data subcarriers of the OFDM symbol implemented using an IFFT to create real or complex baseband signal. Fig 2 and Fig 3 depict the encoding and decoding process for the scrambled PSDU respectively.

III. DCM AND 16-QAM

A. DCM

The DCM is used as a four-dimensional constellation for data rates 320, 400 or 480 Mb/s. 1200 interleaved and coded bits from the bit interleaver are divided into groups of 200 bits, and then further grouped into 50 groups of 4 reordering bits being mapped onto two QPSK symbols. Then the DCM mapper uses a DCM mixing matrix to execute mapping of the two QPSK symbols into two DCM symbols. The resulting DCM symbols are formed into two 16-point constellations and then mapped onto two individual OFDM data subcarriers with 50 OFDM data subcarriers separation. Each OFDM subcarriers occupies a bandwidth of

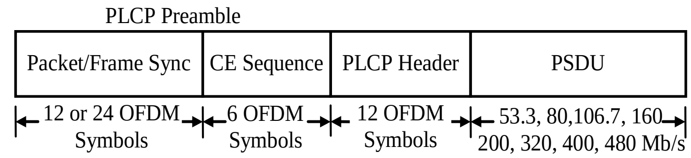

Fig. 1. PPDU structure [3]

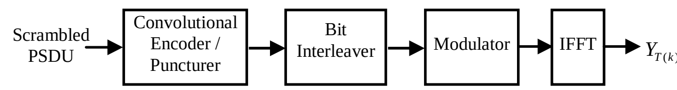

Fig. 2. Encoding process for the scrambled PSDU at Transmitter [3]

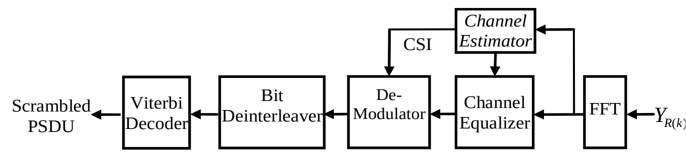

Fig. 3. Decoding process for the scrambled PSDU at Receiver

MHz (528 MHz / 128). Therefore the bandwidth between the two individual OFDM data subcarriers related to the two complex numbers is at least 200 MHz, which offers good frequency diversity gain against channel deep fading.

To demap the DCM symbols at the receiver, the received and equalized symbols can be demapped by using Maximum Likelihood (ML) soft bit or Log-Likelihood Ratio (LLR) demapping methods with the aid of Channel State Information (CSI) as further decoding enhancement technique. In DCM scheme, the code rate is high and no spreading is applied. The soft bits from the DCM demapper are then input to the bit deinterleaver, the soft bit Viterbi decoder and then descrambled to recover the PSDU. The achievable system performance for 8% Packet Error Rate (PER) [7] is approximately 3.9 meters at 480 Mb/s by using both of the aforementioned methods [8] with an implementation loss included of 2.5 dB. However the soft bit demapping method offers lower computation complexity and extremely reduces hardware implementation cost [9].

B. 16-QAM

Two 16-QAM-like constellation mappings are used in the DCM. Obviously if only one 16-QAM-like constellation mapping is used for the modulation system then this would result in less reliability but twice the number of bits can be transmitted per subcarrier resulting in faster throughput. Rectangular Gray coded 16-QAM, as illustrated in Fig. 4, can be proposed as a modulation scheme to increase the system throughput. In the DCM approach, 4 bits from a group of 200 coded and interleaved bits are modulated into two different symbols which are mapped onto two different OFDM data subcarriers. If the 16-QAM is used, 4 coded and interleaved bits are mapped into one symbol, and then this symbol is mapped onto one data subcarrier within

an OFDM symbol. Consequently, 400 coded and interleaved bits are required to map onto 100 OFDM data subcarriers within an OFDM symbol, and data rate of which DCM is used can be doubled.

Rectangular Gray coded 16-QAM can be proposed as a modulation scheme to increase the system throughput. If the 16-QAM is employed instead of DCM, the four coded and interleaved bits modulated onto one symbol can be mapped onto one data subcarrier. Consequently, 400 coded bits are required to map onto 100 OFDM data subcarriers within an OFDM symbol. As a result, the 16-QAM can increase the system throughput from 640 Mb/s to 960 Mb/s comparing to DCM 320 Mb/s to 480 Mb/s mode (Appendix A).

To demap the 16-QAM, soft demapping can be used resulting in maximizing the post 16-QAM baseband processing. The four soft bits are demapped as described in (1)-(4), where $I_{R(k)}$ and $Q_{R(k)}$ are the real part and imaginary part of the equalized symbol. The CSI can also be applied to 16-QAM soft demapping to achieve further demapping performance improvement. However, the information is no longer mapped onto two different OFDM subcarriers as in the DCM, thus there is no need to compare and select more reliable CSI from the different associated OFDM data subcarriers. Therefore the CSI associated to each OFDM data subcarrier is the LS based CSI averaged from six blocks of CE sequences with band hopping scheme, and then directly multiply with the corresponding soft bit to produce more reliable soft bit value, as described in (5)-(8).

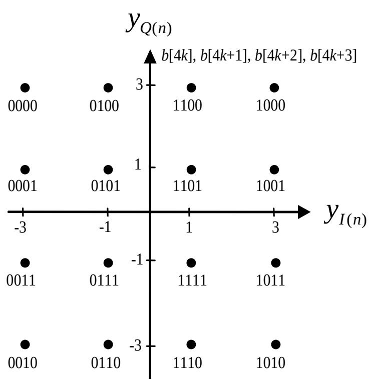

Fig. 4 Rectangular Gray coded16-QAM

$$Soft(b_{4k}) = I_{R(k)} \quad k = 0, 1\ldots99 \tag{1}$$

$$Soft(b_{4k+1}) = \begin{cases} 2 + I_{R(k)} & if\,(I_{R(k)} \le 0) \\ 2 - I_{R(k)} & if\,(I_{R(k)} > 0) \end{cases} \tag{2}$$

$$Soft(b_{4k+2}) = -Q_{R(k)} \tag{3}$$

$$Soft(b_{4k+3}) = \begin{cases} 2 + Q_{R(k)} & if\,(Q_{R(k)} \le 0) \\ 2 - Q_{R(k)} & if\,(Q_{R(k)} > 0) \end{cases} \tag{4}$$

$$Soft(b_{4k}) = I_{R(k)} \times CSI_k \qquad k = 0, 1\ldots99 \tag{5}$$

$$Soft(b_{4k+1}) = \begin{cases} \left(2 + I_{R(k)}\right) \times CSI_k & if\,(I_{R(k)} \le 0) \\ \left(2 - I_{R(k)}\right) \times CSI_k & f\,(I_{R(k)} > 0) \end{cases} \tag{6}$$

$$Soft(b_{4k+2}) = -Q_{R(k)} \times CSI_k \tag{7}$$

$$Soft(b_{4k+3}) = \begin{cases} \left(2 + Q_{R(k)}\right) \times CSI_k & if\,(Q_{R(k)} \le 0) \\ \left(2 - Q_{R(k)}\right) \times CSI_k & if\,(Q_{R(k)} > 0) \end{cases} \tag{8}$$

However there is no successful link under multipath interference (Forester's Channel Model 1 CM1[10]) transmitting at 960 Mb/s or the system has poor performance only achieving 1.0 meters at lower data rate of 640 Mb/s at fixed point model. Hence the rectangular Gray coded 16-QAM is not the ideal modulation scheme for the high data rate MB-OFDM system. To increase the system throughput while fitting into the current MB-OFDM system, a new modulation scheme will be needed.

IV. Dual Circular 32-QAM

A. *DC 32-QAM mapping*

Since 16-QAM is not a suitable modulation scheme for the high data rate MB-OFDM system, there is no need to consider higher order modulations, for instance 32-QAM, 64-QAM etc. Therefore if a new modulation scheme is proposed to fit into the existing system, the new modulation scheme comprising for an OFDM symbol shall not map the number of bits over 400 bits. Moreover, the new modulation scheme needs to be robust mapping 400 bits or less with successful transmission in a multipath environment. With considering the DCM approach, the two DCM symbols are obtained from two QPSK symbols by multiplying a DCM mixing matrix, which results in the information being mapped into two 16-QAM-like symbols associated with two OFDM data subcarriers receptively. The 8-ary PSK can also be an ideal candidate for a new modulation scheme for the MB-OFDM system. Two 8-ary PSK in conjunction with frequency diversity can be an alternative to the DCM. However it offers lower throughput than the DCM. We might consider using the 8-ary PSK-like constellation as less compact for bits mapped into a symbol; meanwhile the bits in a symbol can be partly transmitted with the frequency diversity. Taking into account with this characteristic, it is possible to create a new modulation scheme.

A Dual Circular (DC) 32-QAM modulator is proposed as an alternative modulation scheme that fits into the existing ECMA-368 standard structure with the objective to map more information bits onto an OFDM symbol, while at the same time providing enough Euclidean symbol distance to maintain successful transmission in multipath environments at the higher data rates. After bit interleaving, 1500 coded and interleaved bits were required to be divided into groups of 250 bits and then further grouped into 50 groups of 5 reordering bits. Each group of 5 bits was represented as ($b_{g(k)}$, $b_{g(k)+50}$, $b_{g(k)+51}$, $b_{g(k)+100}$,

$b_{g(k)+101}$), where $k \in [0\ldots49]$ and

$$g(k)=\begin{cases} 2k & k\in[0\ldots24] \\ 2k+50 & k\in[25\ldots49] \end{cases} \tag{9}$$

Four bits ($b_{g(k)+50}$, $b_{g(k)+51}$, $b_{g(k)+100}$, $b_{g(k)+101}$) are mapped across two QPSK symbols ($x_{g(k)}+jx_{g(k)+50}$), ($x_{g(k)+1}+jx_{g(k)+51}$) as in (10). Those two bits pairs are not in consecutive order within the bit streams. $b_{g(k)+50}$ and $b_{g(k)+100}$ are mapped to one QPSK symbol while $b_{g(k)+51}$ and $b_{g(k)+101}$ are mapped to another QPSK symbol to achieve further bit interleaving against burst errors.

$$\begin{bmatrix} x_{g(k)}+jx_{g(k)+50} \\ x_{g(k)+1}+jx_{g(k)+51} \end{bmatrix}=\begin{bmatrix} (2b_{g(k)+50}-1)+j(2b_{g(k)+100}-1) \\ (2b_{g(k)+51}-1)+j(2b_{g(k)+101}-1) \end{bmatrix} \tag{10}$$

Then these two QPSK symbols are mapped into two DC 32-QAM symbols ($y_{T(k)}$, $y_{T(k+50)}$) depending on value of bit $b_{g(k)}$ as in (11)-(13), where $K_{MOD} = 1/\sqrt{6.175}$ as the normalization factor. Each DC 32-QAM symbol in the constellation mapping has equal decision region for each bit, as in Fig. 5. $b_{g(k)}$, $b_{g(k)+50}$ and $b_{g(k)+100}$ are mapped into symbol $y_{(k)}$, while $b_{g(k)}$, $b_{g(k)+51}$ and $b_{g(k)+101}$ are mapped into symbol $y_{(k+50)}$. It can be seen that 2.5 information bits are mapped onto one OFDM data subcarrier. As a result, $b_{g(k)}$ is related to the DC 32-QAM symbol pair ($y_{(k)}$, $y_{(k+50)}$) mapped onto two OFDM data subcarriers. $b_{g(k)+50}$ and $b_{g(k)+100}$ are only related to $y_{(k)}$ mapped onto one OFDM data subcarrier, while $b_{g(k)+51}$ and $b_{g(k)+101}$ are only related to $y_{(k+50)}$ mapped onto one OFDM data subcarrier as well. Moreover, the constellation points were positioned in circular loci to offer constant power for each DC 32-QAM symbol, which implies less multiple amplitudes used in the modulation offering less impact to the Automatic Gain Control (AGC) and Analogue to Digital Converter (ADC). Each OFDM subcarrier occupies a bandwidth of about 4 MHz, thus the bandwidth between the two individual OFDM data subcarriers related to the two complex numbers $y_{T(k)}$ and $y_{T(k+50)}$ is at least 200 MHz, which offers a frequency diversity against channel deep fading and benefit for bits recovering. Fig. 6 depicts the DC 32-QAM mapping process.

$$\begin{bmatrix} y_{T(k)} \\ y_{T(k+50)} \end{bmatrix}=K_{MOD}\begin{bmatrix} \alpha x_{g(k)}+j\beta x_{g(k)+50} \\ \beta x_{g(k)+1}+j\alpha x_{g(k)+51} \end{bmatrix} \tag{11}$$

where

$$\alpha=\begin{cases} 1 & ,b_{g(k)}=0 \\ 2.275 & ,b_{g(k)}=1 \end{cases} \tag{12}$$

$$\beta=\begin{cases} 2.275 & ,b_{g(k)}=0 \\ 1 & ,b_{g(k)}=1 \end{cases} \tag{13}$$

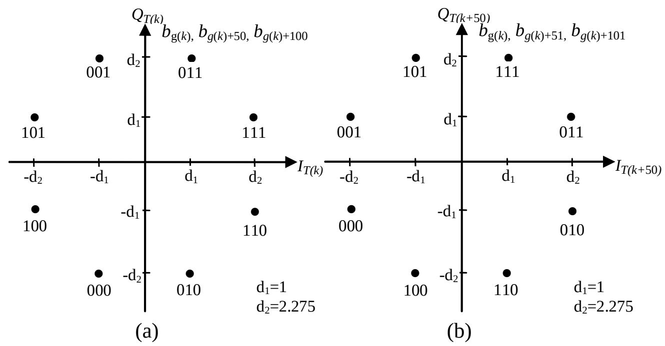

Fig. 5 Dual Circular 32-QAM constellation mapping: (a) mapping for $y_{T(k)}$; (b) mapping for $y_{T(k+50)}$

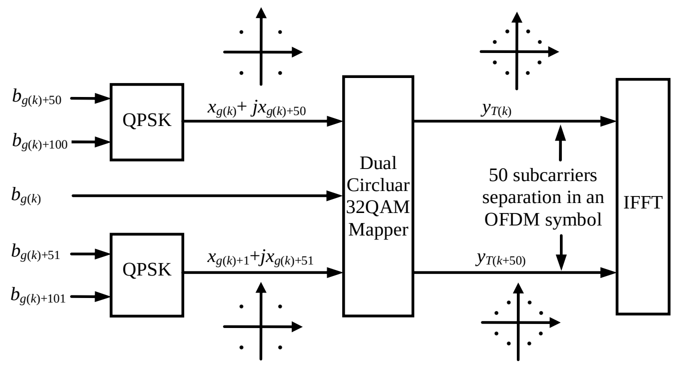

Fig. 6 Dual Circular 32-QAM mapping process

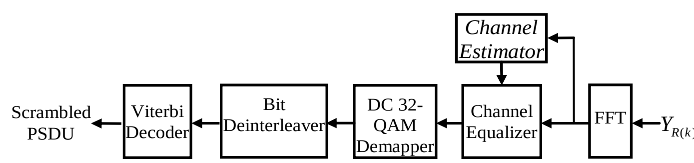

Fig. 7 PSDU Decoding process with DC 32-QAM

B. DC 32-QAM demapping

The proposed DC 32-QAM utilizes soft bit demapping to demap two equalized complex numbers previously transmitted on different data subcarriers into a subgroup of 5 soft bits, and then outputs groups of 250 soft bits. Fig 7 depicts PSDU decoding process with DC 32-QAM.The demapper is proposed to use the DC 32-QAM demapper, and other functional blocks are remained. The demapped and deinterleaved soft bits are input to Viterbi decoder to recover the original information bits. Each soft bit value of $b_{g(k)+50}$, $b_{g(k)+51}$, $b_{g(k)+100}$ and $b_{g(k)+101}$ depend on the soft bit magnitude of the I/Q completely. In addition, each soft bit can be demapped from its associated ($I_{R(k)}$, $Q_{R(k)}$) and ($I_{R(k+50)}$,

$Q_{R(k+50)}$) independently. Furthermore, the demapping performance can remain without using the factor $1/K_{MOD}$. Hence the four soft bit values are given by (14)-(17).

$$Soft(b_{g(k)+50}) = I_{R(k)} \tag{14}$$

$$Soft(b_{g(k)+51}) = I_{R(k+50)} \tag{15}$$

$$Soft(b_{g(k)+100}) = Q_{R(k)} \tag{16}$$

$$Soft(b_{g(k)+101}) = Q_{R(k+50)} \tag{17}$$

To demap $b_{g(k)}$ in the constellation for $y_{R(k)}$, the demapped information bit is considered to be ‘1’ if the received symbol is close to the constellation point along with I axis, otherwise it is ‘0’ if close to the constellation point along with Q axis. However, to demap $b_{g(k)}$ in the constellation for $y_{R(k+50)}$, the demapped information bit is considered to be ‘0’ if the received symbol is close to the constellation point along with I axis, otherwise it is ‘1’ if close to the constellation point along with Q axis. Fig 8 depicts Euclidean distances for a possible received DC 32-QAM symbol pair with region for $b_{g(k)}$. Since the bit regions of $b_{g(k)}$ in the two constellation mapping are different, the associated I and Q value from $y_{R(k)}$ and $y_{R(k+50)}$ cannot be simply combined. Hence the Euclidean symbol distance for each received symbol in the associated constellation mapping is calculated first, as in (15)-(18). Then the two Euclidean symbol distances are summed together as a soft bit value for $b_{g(k)}$, as in (19).

$$L1 = \sqrt{\left(\left|I_{R(k)}\right| - d1\right)^2 + \left(\left|Q_{R(k)}\right| - d2\right)^2} \tag{15}$$

$$L2 = \sqrt{\left(\left|I_{R(k)}\right| - d2\right)^2 + \left(\left|Q_{R(k)}\right| - d1\right)^2} \tag{16}$$

$$L3 = \sqrt{\left(\left|I_{R(k+50)}\right| - d1\right)^2 + \left(\left|Q_{R(k+50)}\right| - d2\right)^2} \tag{17}$$

$$L4 = \sqrt{\left(\left|I_{R(k+50)}\right| - d2\right)^2 + \left(\left|Q_{R(k+50)}\right| - d1\right)^2} \tag{18}$$

$$Soft(b_{g(k)}) = \frac{1}{2} \times (L1 - L2 + L3 - L4) \tag{19}$$

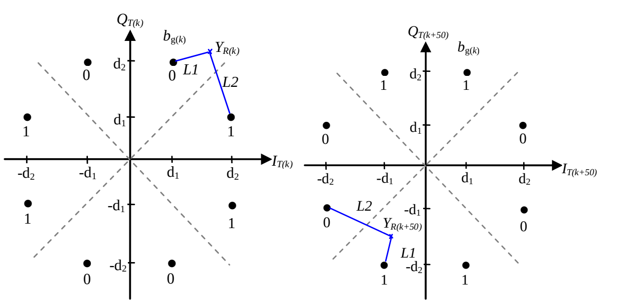

Fig. 8 Symbol distances for a possible received symbol pair $y_{R(k)}$ and $y_{R(k+50)}$ with decision region for $b_{g(k)}$

C. Enhancement by exploiting Channel State Information

In OFDM modulation, the OFDM subcarriers suffer from different effects, caused by for example echoes and deep fading, etc. Particularly the noise effect of the frequency-domain equalization process can degrade the soft decision demapping. Each OFDM subcarrier position has a dynamic estimation for the data reliability, termed as the Channel State Information (CSI), which can be used to enhance the channel decoder’s error correction performance [11]-[13]. Each OFDM data subcarrier has a potentially different CSI. The more CSI measurement that can be taken, the more reliable the CSI estimation is in the presence of thermal noise offering better decoding result.

The proposed CSI aided scheme coupled with the band hopping information maximizes the DCM soft demapping performance [14]. $b_{g(k)}$ mapped to two symbols are mapped onto two OFDM data subcarriers resulting two CSI from the two associated OFDM data subcarriers. If a smaller or larger CSI value is chosen as a reliable scale term, it causes inequality of signal power for the different OFDM data subcarriers. The averaging CSI is adopted for $b_{g(k)}$. As a result, the five soft bits incorporated with CSI for the DC 32-QAM demapping are given by the following:

$$Soft(b_{g(k)}) = \left(\frac{L1 - L2 + L3 - L4}{2}\right) \times \left(\frac{CSI_k + CSI_{k+50}}{2}\right) \tag{20}$$

$$Soft(b_{g(k)+50}) = I_{R(k)} \times CSI_k \tag{21}$$

$$Soft(b_{g(k)+51}) = I_{R(k+50)} \times CSI_{k+50} \tag{22}$$

$$Soft(b_{g(k)+100}) = Q_{R(k)} \times CSI_k \tag{23}$$

$$Soft(b_{g(k)+101}) = Q_{R(k+50)} \times CSI_{k+50} \tag{24}$$

V. CONSEQUENTIAL BIT INTERLEAVER

Since the DC 32-QAM can map more information bits than the DCM, the structure of bit interleaver in ECMA-368 needs to be extended. The proposed bit interleaver shall interleave 1500 coded bits and output to the DC 32-QAM modulator (see Appendix). The proposed bit interleaving operation is performed in two stages being symbol interleaving and intra-symbol tone interleaving to provide robustness against bust errors, as illustrated in Fig 9.

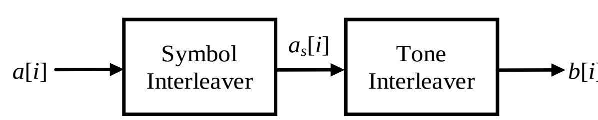

Fig.9 Consequential bit interleaver for DC 32-QAM

In the symbol interleaving operation, the coded bits are grouped into blocks of N_{CBP6S} (N_{CBP6S} = 1500) bits which compose six OFDM symbols. Then the N_{CBP6S} bits are permuted by using a block interleaver of size N_{CBPS} (N_{CBPS} = 250) by $6/N_{TDS}$ (N_{TDS} = 1) across six consecutive OFDM symbols resulting in frequency diversity within a band group. The output of the symbol interleaver block is described in the following.

$$a_s[i] = a\left[\left\lfloor \frac{i}{N_{CBPS}} \right\rfloor + \left(\frac{6}{N_{TDS}}\right) \times \mathrm{mod}(i, N_{CBPS})\right] \qquad (25)$$

where $a[i]$ and $a_s[i]$ is input and output bit sequences of the symbol block interlaever respectively, and $i = 0, \ldots, N_{CBP6S}$-1. $\lfloor . \rfloor$ is the floor function returning the largest integer value less than or equal to the argument value. The mod(a,b) function returns the non-negative integer remainder when a is divided by b.

In the intra-symbol tone interleaving operation, the output of the symbol interlaver grouped into blocks of N_{CBPS} bits is permuted by using a regular block intra-symbol interleaver of size N_{Tint} ×10 (N_{Tint} = 25) resulting in frequency diversity across data subcarriers within an OFDM symbol and offering robustness against narrow-band interferes. The output of the tone interleaver, $b[i]$, is described in the following.

$$b[i] = a_s\left[\left\lfloor \frac{j}{N_{T\,\mathrm{int}}} \right\rfloor + 10 \times \mathrm{mod}(j, N_{T\,\mathrm{int}})\right] \qquad (26)$$

where $j = 0, \ldots, N_{CBP6S}$-1 and $N_{TDS} = 1$

In ECMA-368, the bit interleaver is required to use an intra-symbol cyclic shifters block after the tone interleaver block, when only the TDS and FFI modes are enabled. However these modes are not required when the system is operated with the proposed DC 32-QAM. Therefore the intra-symbol cyclic shifter is not used in the proposed consequential bit interleaver.

VI. SYSTEM PERFORMANCE MEASUREMENTS AND COMPARISONS

A. Propagation distance measurement

The received signal power is calculated the difference between the total transmit power and path loss. Since the FCC defines the average power as 1mW per Megahertz, the total transmitted power can be obtained from the PSD and the operating bandwidth. The total transmitted power P_{TX} can be described in (27) assuming no power loss at the transmitter and 0 dBi transmit antenna gain.

$$P_{TX} = -41.25 + 10\log_{10}(f_U - f_L) \text{ dBm} \qquad (27)$$

where -41.25 dBm/MHz is the UWB EIRP/MHz, f_L = 3168 MHz is the lower frequency of the operating bandwidth, f_U is upper frequency varying from BG1 to BG6. However, BG1 is targeted for the first generation UWB devices and is also a mandatory mode, thus f_U = 4752 MHz is assigned.

The free-space propagation model is defined under IEEE 802.15.3a, which specifies the path loss attenuating the transmitted signal as a function of the lower and upper frequencies of the operating bandwidth. The path loss P_L can be expressed as the following:

$$P_L = 20\log_{10}\left(\frac{4\pi f_g d}{c}\right) \text{ dB} \qquad (28)$$

where f_g = 3882 MHz is the geometric mean of the lower and upper frequencies in BG1. The geometric mean offers a more reasonable value for the expected path loss in the system [12]. d is the distance measured in meters between the transmitter and receiver. $c = 3\text{x}10^8$ m/s is the speed of light.

As a result, the function of received signal power, as described in (29), can be derived from (27) and (28) with transmit and receiver antenna gain (G_T, G_R).

$$P_{RX} = P_{TX} + G_T + G_R - P_L \text{ dBm} \qquad (29)$$

B. Simulation Configuration

The system is simulated in a realistic multipath channel environment of 100 channel realizations in Foerster's Channel Model 1 (CM1) [10] with conformance test requirement in ECMA-368. All simulations results are averaged over 2000 packets with 1024 octets per payload in the PSDU and 90th-percentile channel realization (the worst 10% channels are discarded). The link success probability is defined as the 90th-percentile of channel realizations for which system can successfully acquire and demodulate a packet with a Packet Error Rate (PER) (a packet is in error if at least one bit is in error) of less than 8% [7]. We maintain strict adherence to timing (no frequency offset and perfect OFDM symbol timing) and use a hopping characteristic of Time Frequency Code (TFC)=1, and incorporate 2.5 dB implementation loss [7] in the fixed point model, which raises practical loss due to quantization errors [15]-[17]. The fixed point model is presented using:

i.) Receiver ADC=6 bits;

ii.) ii.) FFT precision=8bit;

iii.) iii.) Chanel estimator precision=12 bits;

iv.) iv.) CSI precision=12 bits;

v.) Equalizer precision=14 bits;

vi.) vi.) Soft-bit (Deinterleaver and Viterbi Decoder) width=12 bits.

C. System performance DC 32-QAM

If CSI is not incorporated into DC 32-QAM demapper, the system can achieve successful transmission in approximately 3.0 meters, thus losing some performance gains, as illustrated in Fig 10. Frequency diversity can enhance DC 32-QAM performance by mapping the coded information onto two different OFDM subcarriers with 200 MHz bandwidth separation. Without this large bandwidth separation, the information mapped in adjacent data subcarriers in each OFDM symbol will have more has no robustness against channel deep fading and no signal compensation from the associated CSI, particularly leading to no advantage of $b_{g(k)}$ mapped into two DC 32-QAM symbol associated with two OFDM data subcarriers. As a result the system performance drops by 0.9 meters to only achieve approximately 2.3 meters, as illustrated in Fig 10.

To compare 16-QAM, DC 32-QAM and DCM performance,

the system is set to the same configuration with the same coding rate. With changing the modulation scheme and the associated bit interleaver, the system throughput can be increased to 600 Mb/s and 960 Mb/s by DC 32-QAM and 16-QAM respectively, while the system using DCM performs 480 Mb/s.

As seen from Fig 11, the DC 32-QAM offers a successful link with a close performance to the DCM. There is no successful link if 16-QAM is used at 960 Mb/s. Alternatively, lowering the data rate to 640 Mb/s by changing the coding scheme (Appendix A), the system performance is only 1 meter. However, by implementing the DC 32-QAM scheme presented in this paper offers 3 meters at 600 Mb/s while the existing system using DCM can be achieved 3.8 meters at 480 Mb/s. The effective 600 Mb/s performance in practical multipath environment with moderate packet loss can offer an actual effective data rate at 480 Mb/s.

VII. CONCLUSION

Wireless-USB has now been standardized to use the services of Multiband OFDM (ECMA-368) as the transport mechanism. ECMA-368 offers a robust wireless solution and low cost wireless service in WPAN. This paper has been proposed a cost-effective and high performance modulation scheme as termed DC 32-QAM that can fit into the configuration of ECMA-368 standard. This alternative modulation scheme can increase the system throughput to 600 Mb/s with outputting constant modulated symbol power, which is of great benefit to the AGC and ADC, resulting in a successful link of 3 meters in multipath environments. Thereby an effective data rate of 480 Mb/s can be achieved with moderate packet loss, even offer a higher throughput for comparable propagation conditions.

APPENDIX

A. PSDU rate-dependent Parameters

Data Rate (Mb/s)	Modulation	Coding Rate (R)	Frequency Domain Spreading	Time Domain Spreading	Coded Bits / 6 OFDM symbol(N_{CBP6S})
53.3	QPSK	1/3	YES	YES	300
80	QPSK	1/2	YES	YES	300
106.7	QPSK	1/3	NO	YES	600
160	QPSK	1/2	NO	YES	600
200	QPSK	5/8	NO	YES	600
320	DCM	1/2	NO	NO	1200
400	DCM	5/8	NO	NO	1200
480	DCM	3/4	NO	NO	1200
600	Dual Circular 32-QAM	3/4	NO	NO	1500
640	16-QAM	1/2	NO	NO	2400
960	16-QAM	3/4	NO	NO	2400

B. Parameters for bit interleaver

Data Rate (Mb/s)	Time Domain Spreading Factor (NTDS)	Coded Bits / OFDM Symbol (NCBPS)	one Interleaver lock Size (NTint)	Cyclic Interleaver Shift (Ncyc)
53.3	2	100	10	33
80	2	100	10	33
106.7	2	200	20	66
160	2	200	20	66
200	2	200	20	66
320	1	200	20	33
400	1	200	20	33
480	1	200	20	33
600	1	250	25	-

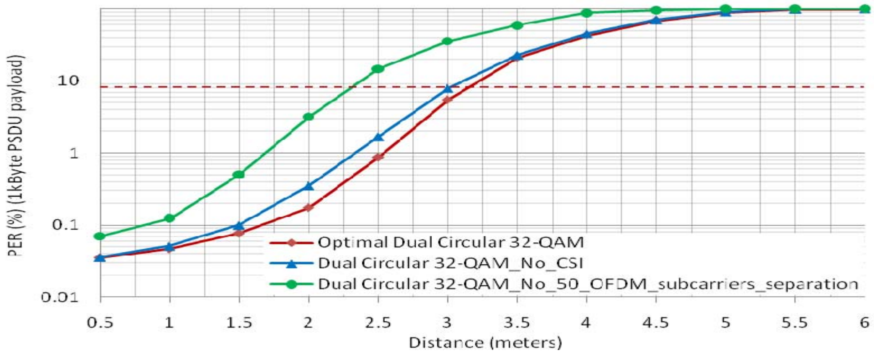

Fig. 10 Performance gain for Dual Circular 32-QAM using frequency diversity and CSI

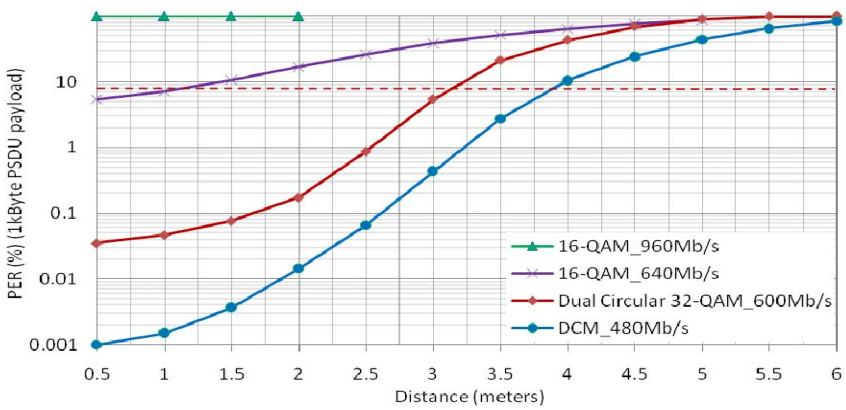

Fig. 11 Fixed point system performance (in CM1) comparisons for 16-QAM, Dual Circular 32-QAM and DCM

REFERENCES

[1] J. Axelson, *USB Complete*, Lakeview Research, Second Edition, ISBN 0965081958, 2001

[2] USB-IF. Certified Wireless USB. http://www.usb.org/developers/wusb/

[3] WiMedia Alliance http://www.wimedia.org/en/index.asp

[4] ECMA-368, "High rate ultra wideband PHY and MAC standard," 1st Edition, December 2007.

[5] ECMA-368, "High rate ultra wideband PHY and MAC standard, 3rd Edition, December 2008, also maintained as ISO/IEC 26907

[6] R. S. Sherratt and R. Yang, "A dual QPSK soft-demapper for multiband OFDM exploiting time-domain spreading and guard interval diversity," *IEEE Transactions on Consumer Electronics, vol. 53, no.1, pp. 46-49, February 2007*

[7] MBOA standard "MultiBand OFDM Physical Layer Proposal for IEEE 802.15.3a," *September 2004,*

http://www.wimedia.org/imwp/idms/popups/pop_download.asp?ContentID=6516

[8] R. Yang and R. S. Sherratt, "Dual carrier modulation demapping methods and performances for Wireless USB," the 9th Annual Postgraduate Symposium (PGNET 2008), Liverpool,UK, June 2008

[9] R. Yang, R. S. Sherratt and O. Cadenas, "FPGA Based Dual Carrier Modulation Soft Mapper and Demapper for the MB-OFDM UWB Platform," EPSRC 8th Annual Postgraduate Symposium (PGNET 2007), Liverpool,UK, June 2007

[10] J. Foerster, "Channel Modeling Sub-committee Report Final," IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), IEEE P802.15-02/490-SG3a. 7th February 2003 http://grouper.ieee.org/groups/802/15/pub/2003/Mar03/02490r1P802-15_SG3a-Channel-Modeling-Subcommittee-Report-Final.zip

[11] M. R. G. Butler, S. Armour, P. N. Fletcher, A. R. Nix, and D. R. Bull, "Viterbi decoding strategies for 5 GHz wireless LAN systems," in Proc. IEEE 54th Veh. Technol. Conf., VTC 2001 Fall, pp. 77 –81

[12] W. Lee, H. Park, and Park J., "Viterbi decoding method using channel state information in COFDM system," IEEE Transactions on Consumer Electronics, vol. 45, no. 3, pp. 533-537, August 1999.

[13] W. Li, Z. Wang, Y. Yan and M. Tomisawa, "An efficient low-cost LS equalization in COFDM based UWB systems by utilizing channel-state-information (CSI)," *Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd,* Sept, 2005, *Vol. 4, pp. 67-71*

[14] R. Yang and R. S. Sherratt, "An Improved DCM Soft-Demapper for the MB-OFDM UWB Platform Exploiting Channel-State-Information," *IEEE/IET Signal Processing for Wireless Communications, London, 6-8 June 2007*

[15] R. S. Sherratt and S. Makino, "Numerical Precision Requirements on the Multiband Ultra-Wideband System for Practical Consumer Electronic Devices," *IEEE Transactions on Consumer Electronics*, vol 51(2), pp 368-392, May 2005

[16] R. S. Sherratt, O. Cadenas and R. Yang, "A Practical Low Cost Architecture for a MB-OFDM Equalizer (ECMA-368)," *11th Annual IEEE International Symposium of Consumer Electronics (ISCE 2007), Texas, US, June 2007*

[17] R. Yang, B. Yong, C. Lian, "Fixed Point Dual Circular 32-QAMPerformance for Wireless USB", IEEE Consumer Electronics, Communications and Networks (CECNet 2011), Xianning, China, 16-18 April, 2010